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Effect of Copper on the Aging Characteristics of Cu-Ni Structural Steels

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ATLSS Report No. 00-02

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ABSTRACT

In previous ATLSS studies, improved fracture toughness and weldability of 80W, 90W, and 100W copper-nickel bridge/infrastructure steels were demonstrated with existing 80-, 90-, or 100-ksi (550, 620, or 690 MPa) yield strength structural weathering steels. The improvements result from the strengthening of the Cu-Ni steels by copper precipitation as well as by conventional transformation to low-temperature microconstituents. This dual-strengthening permits a significant reduction in carbon content and the resultant superior toughness and weldability of the Cu-Ni steels. In a further study of the composition of Cu-Ni steels, the effect of copper-content variation on hardenability and mechanical properties was investigated. Equally important, is the effect of copper content on the aging characteristics of this type of precipitation-strengthened steel. Therefore, the study of the effect of copper content was extended in the present study to determine the time-temperature relations on the aging characteristics of the Cu-Ni steels having copper contents in the range 0.25 to 1.20 percent.

For the class of steels investigated as candidates for a 100W bridge steel, the following conclusions were drawn:

1. a copper content of about 1.0 percent was adequate to maximize precipitation strengthening,

2. the hardness due to copper precipitation strengthening exhibited the greatest increase at 950F (510C), was not altered appreciably at 1050 or 1150F (565 and 620C), but decreased progressively with time at 1250F (675C),

3. with respect to the effect of time on copper precipitation strengthening and softening of the MA constituent, the following was observed:

a. at 950F (510C), strengthening occurred for four hours,

b. at 1250F (675C), softening occurred progressively for eight hours,

c. at 1050 and 1150F (565 and 620C), strengthening and softening essentially balanced each other over the total aging time.

INTRODUCTION

On the basis of previous ATLSS studies[1,*], the improved fracture toughness and weldability of 80W, 90W, and 100W copper-nickel bridge/infrastructure steels were compared with existing 80-, 90-, or 100-ksi (550, 620, or 690 MPa) yield strength structural weathering steels. The improvements result from the strengthening of the Cu-Ni steels by copper precipitation as well as by conventional transformation to low-temperature microconstituents. This dual-strengthening permits a significant reduction in carbon content and the resultant superior toughness and weldability of the Cu-Ni steels. To further study the composition of Cu-Ni steels, the effect of copper content on hardenability and mechanical properties was investigated[2]. Of equal importance is the effect of copper content on the aging characteristics of this precipitation-strengthened steel. Therefore, the study of the effect of copper content was extended in the present study to determine the time-temperature relations on the aging characteristics of the Cu-Ni steels listed in Table I.

EXPERIMENTAL PROCEDURE

MELTING AND ROLLING

A 300-pound (135 kg) heat was vacuum-melted and poured into three 100-pound (45 kg) ingots with additions to the second and third ingot to obtain the compositions shown in Table I and identified as Steels M1, M2, and M3. The ingots were charged into a reheat furnace at 2150F (1175C), rolled in five passes to 1-inch-thick (25mm) plate with a finishing temperature of approximately 1750F (950C) and air cooled. Previously, in a similar way steels from prior studies were produced and Steel B6 was included in the present study. The chemical composition and metallurgical characteristics of the various steels are listed in Tables I and II, respectively.

HEAT TREATMENT

For each of the three M steels and Steel B6, a 1-inch-thick plate was austenitized at 1650F (900C) and immersion-quenched in a 70F (20C) water bath [H=1.5, cooling rate of 50F/sec (28C/sec)] to simulate production quenching of a 1-inch-thick (25mm) plate. Also, a 1-inch-thick plate for each of the four steels was normalized by air cooling from 1650F (900C) at 1F/sec (0.55C/sec). The procedures employed have been previously described[1,2]

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*See references

SPECIMEN PREPARATION AND AGING TREATMENTS

For Steels M1, M2, M3, and B6, 40 test coupons, 3/8-inch thick by 1-inch long were cut from the 1-inch plate thickness. Five quenched coupons and five normalized coupons for each steel were aged at 950F, 1050F, 1150F, or 1250F (510C, 565C, 620C, or 675C). At each temperature, one water-quenched and one normalized coupon was removed and quenched upon reaching the aging temperature (15 minutes), and subsequent coupons were removed after an additional 1, 2, 4, or 8 hours. The hardness of each coupon was measured prior to aging and after the various aging treatments.

METALLOGRAPHIC EVALUATION

For Steels M1, M2, M3, and B6, a sample in the as-normalized and one in the as-water-quenched condition was polished, etched and photographed. This was repeated for the four steels after aging at 1250F (675C) for eight hours.

RESULTS AND DISCUSSION

EFFECT OF COMPOSITION ON AGING

The effect of copper content on the aging response of the four steels is illustrated in Figures 1, 2, 3, and 4 for Steels M1, M2, B6, and M3, respectively, As-normalized, the Steel M1, Figure 1A, responds to the aging temperatures and times as might be expected from its low copper content. No aging is produced by exposure to 950 or 1050F (510 or 565C), but a mild secondary hardening occurs at 1150F (620C), probably contributed by the vanadium content, whereas, aging the as-quenched Steel M1 at 950, 1050, or 1150F (510, 565, or 620C) did not alter the hardness appreciably, Figure 1B, However, at 1250F (675C), significant softening occurred progressively with time.

The normalized Steel M2 contained enough copper, 0.75% to produce significant precipitation strengthening at 950F (510C) after 4 and 8 hours aging, and at 1050 and 1150F (565 and 620C), the strengthening was sufficient to offset any softening of the second phase, martensite-austenite, MA, constituent, Figure 2A. At 1250F (675C), however, the hardness decreased progressively with time as a result of the softening of the MA consituent and overaging of the copper precipitate. A somewhat similar aging response was observed for the as-quenched Steel M2, Figure 2B, in that some net strengthening occurred at 950 and 1050F (510 and 565C), essentially no net effect at 1150F (620C) and progressive softening at 1250F (675C).

The normalized Steels B6 and M3, Figures 3A and 4A, strengthened noticeably at 950F (510C), were essentially unchanged in hardness at 1050F (565C), softened moderately at long times at 1150F (620C), and again softened progressively at 1250F (675C). The as-quenched Steels B6 and M3, Figures 3B and 4B, showed hardness changes similar to those for the normalized steels except that they began and remained at significantly higher hardness levels.

EFFECT OF TIME AND TEMPERATURE ON AGING

The effects of temperature, time, and copper content on aging at 950F, 1050F, 1150F, or 1250F (510C, 565C, 620C, or 675C) of the four steels is more conveniently illustrated in Figures 5, 6, 7, and 8 respectively. With respect to temperature, maximum precipitation strengthening occurred at 950F (510C) after two hours. For the compositions investigated, maximum precipitation strengthening occurred at 1.00 percent copper and appeared to plateau above 1.00 percent.

With respect to the effect of time on precipitation strengthening and softening of the MA constituent, at 950F (510C), strengthening occurred for four hours, at 1250F (675C), softening occurred continuously for eight hours, and at 1050 and 1150F (565 and 620C), strengthening and softening balanced each other over the total aging time.

It should be remembered that hardness (i.e. strength) is only one property affected by aging; other characteristics such as notch toughness also vary with aging treatments, often inversely to strength.

METALLOGRAPHIC EXAMINATION

The as-normalized microstructures, Figure 9, contained increased amounts of second phase as the copper content increased from 0.25 to 1.20 percent copper, which was mostly agglomerated in the ferrite matrix phase after aging at 1250F (675C) for 8 hours

As water-quenched, the steels exhibited a predominantly granular bainite microstructure, Figure 10, which was largely agglomerated by aging at 1250F (675C) for 8 hours.

CONCLUSIONS

For the class of steels investigated as candidates for a 100W bridge steel, the following conclusions were drawn:

1. A copper content of about 1.0 percent was adequate to maximize precipitation strengthening.

2. The hardness due to copper precipitation strengthening exhibited the greatest increase at 950F (510C), was not altered appreciably at 1050 or 1150F (565 and 620C), but decreased at 1250F (675C).

3. With respect to the effect of time on copper precipitation strengthening and softening of the MA constituent, the following was observed:

a. at 950F (510C), strengthening occurred for four hours,

b. at 1250F (675C), softening occurred progressively for eight hours,

c. at 1050 and 1150F (565 and 620C), strengthening and softening essentially balanced each other over the total aging time.

REFERENCES

1. Gross, J.H., Stout, R.D., and Dawson, H.M., "Copper-Nickel High Performance 70W/100W Bridge Steels - Part II", ATLSS Report 98-02, May 1998.

2. Dawson, H.M., Gross, J.H., and Stout, R.D., "Effect of Copper on the Properties of Copper-Nickel Strtuctural Steels", ATLSS Report 99-08, November 1999.

ACKNOWLEDGEMENT

Melting and rolling of the experimental steels was performed by the U.S. Steel Technical Center.

Table I - Chemical Composition of Steels A, B, E, F, and M

	A4	A6	A8	B4	B6	B8	E4	E6	E8	F4	F6	F8	M1	M2	M3
C	0.045	0.064	0.082	0.043	0.061	0.080	0.042	0.060	0.076	0.040	0.059	0.081	0.059	0.059	0.058
Mn	1.00	1.01	1.00	1.01	1.02	1.01	1.52	1.52	1.50	1.51	1.50	1.49	0.99	1.00	0.99
P	0.012	0.013	0.013	0.010	0.011	0.010	0.011	0.011	0.012	0.010	0.011	0.011	0.012	0.012	0.012
S	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.0035	0.0035	0.0030
Si	0.23	0.23	0.24	0.26	0.27	0.26	0.25	0.26	0.27	0.25	0.25	0.25	0.25	0.25	0.25
Cu	1.02	1.02	1.02	1.00	1.01	1.00	1.00	1.02	1.02	0.99	0.99	0.99	0.25	0.74	1.20
Ni	0.75	0.74	0.75	0.75	0.77	0.76	0.77	0.80	0.81	0.78	0.78	0.77	0.74	0.74	0.73
Cr	0.50	0.50	0.50	0.51	0.51	0.51	0.51	0.51	0.52	0.50	0.50	0.50	0.49	0.49	0.49
Mo	0.24	0.24	0.24	0.50	0.50	0.50	0.25	0.26	0.26	0.51	0.50	0.50	0.49	0.49	0.49
V	0.057	0.056	0.056	0.054	0.054	0.054	0.059	0.057	0.056	0.059	0.059	0.059	0.056	0.057	0.056
Cb	0.015	0.015	0.015	0.018	0.017	0.018	0.016	0.016	0.016	0.017	0.017	0.016	0.015	0.015	0.015
Al (Total)	0.022	0.020	0.019	0.024	0.015	0.012	0.025	0.021	0.019	0.022	0.026	0.025	0.03	0.029	0.027

Table II - Calculated Metallurgical Characteristsics

	A4	A6	A8	B4	B6	B8	E4	E6	E8	F4	F6	F8	M1	M2	M3
DI - ASTM	0.85	1.20	1.56	1.00	1.60	2.20	1.10	1.70	2.30	1.5	2.3	3.2	1.23	1.42	1.60
A_{e1}, F	1325	1325	1325	1320	1320	1320	1305	1305	1305	1305	1305	1305	1320	1320	1320
A_{e3}, F	1560	1540	1525	1565	1545	1530	1540	1525	1510	1540	1530	1510	1570	1550	1540
M_s, F	900	885	860	895	875	855	895	875	860	890	875	850	900	895	870
C.E. (IIW)	0.53	0.55	0.57	0.54	0.56	0.58	0.57	0.59	0.61	0.62	0.64	0.66	0.51	0.54	0.57

A_{e1}, F = 1333 - 25 x %Mn - 26 x %Ni + 40 x %Si +42 x %Cr

A_{e3}, F = $1670 - (876C - 772C^2) - 45Mn - 36Cu - 40Ni - 20Cr + 108Si + 1260P + 450Al$

M_s, F = 955 - 815 x %C - 31 x %Ni + 27 x %Cr - 17 x %Mo + 390 x $\%C^2$

C.E. (IIW) = C (Si+Mn)/6 + (Cu+Ni)/15 + (Cr+Mo+V)/5

Extrapolated Martensitic Hardness, HRc*

%C	95% Martensite	99.9% Martensite
0.04	30.0	35.0
0.06	31.2	36.2
0.08	32.5	37.5
0.10	33.8	38.7

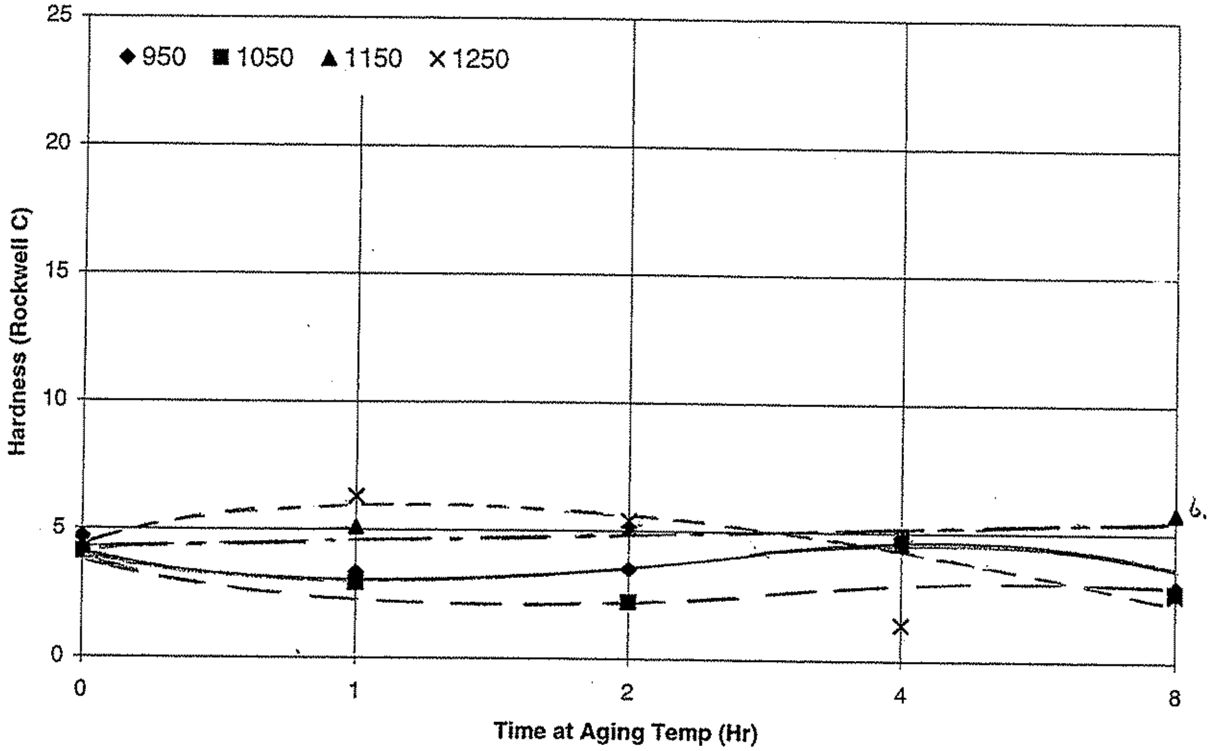

Figure 1a - The Effect of Aging Time and Temperature on Hardness of Steel M1, Normalized

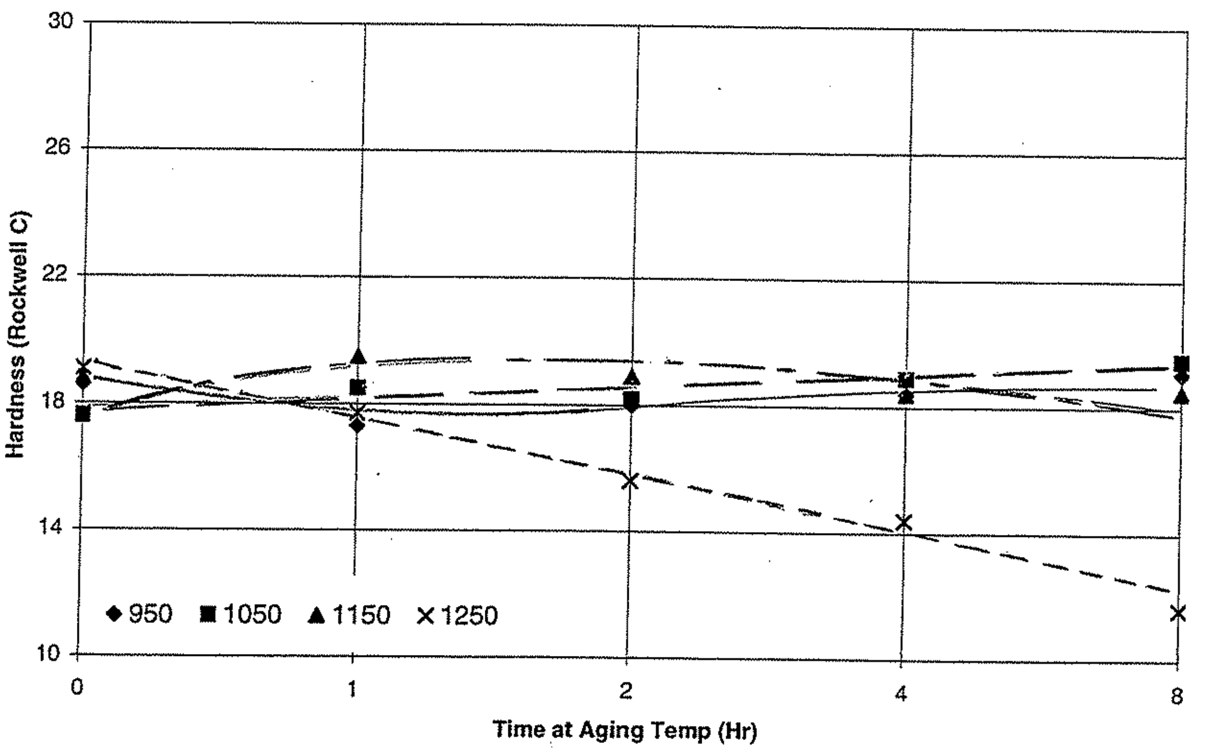

Figure 1b - The Effect of Aging Time and Temperature on Hardness of Steel M1, Water Quenched

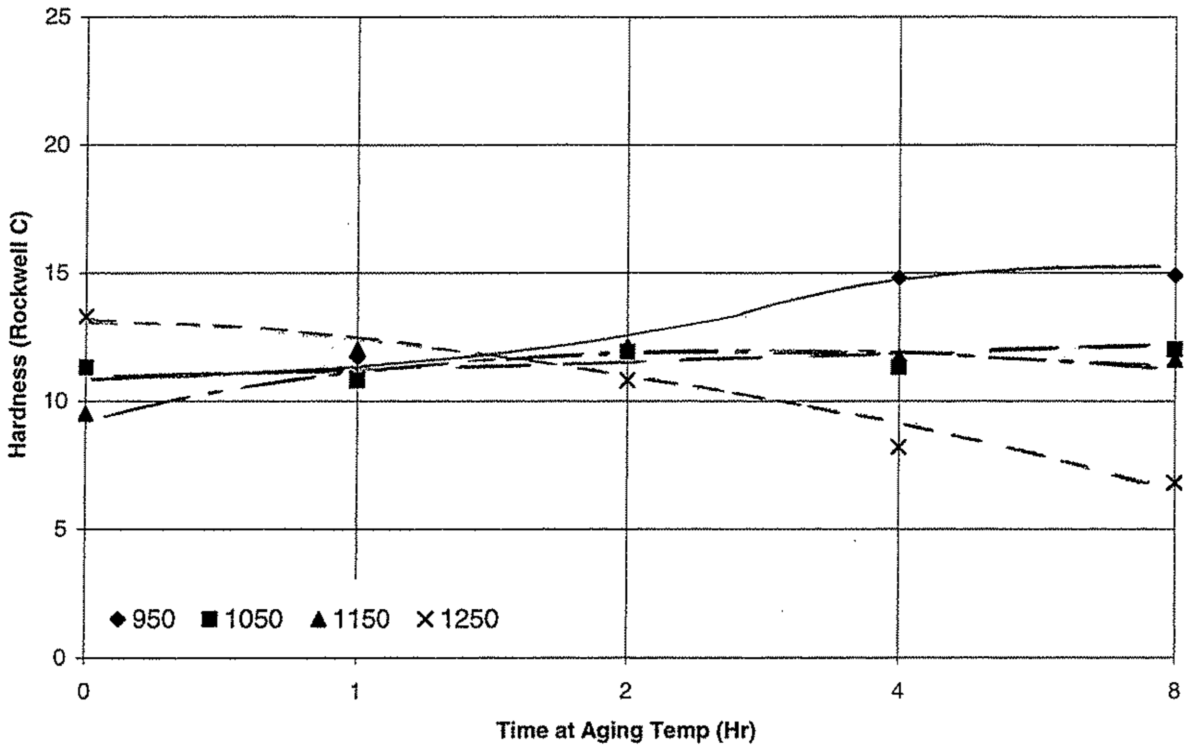

Figure 2a - The Effect of Aging Time and Temperature on Hardness of Steel M2, Normalized

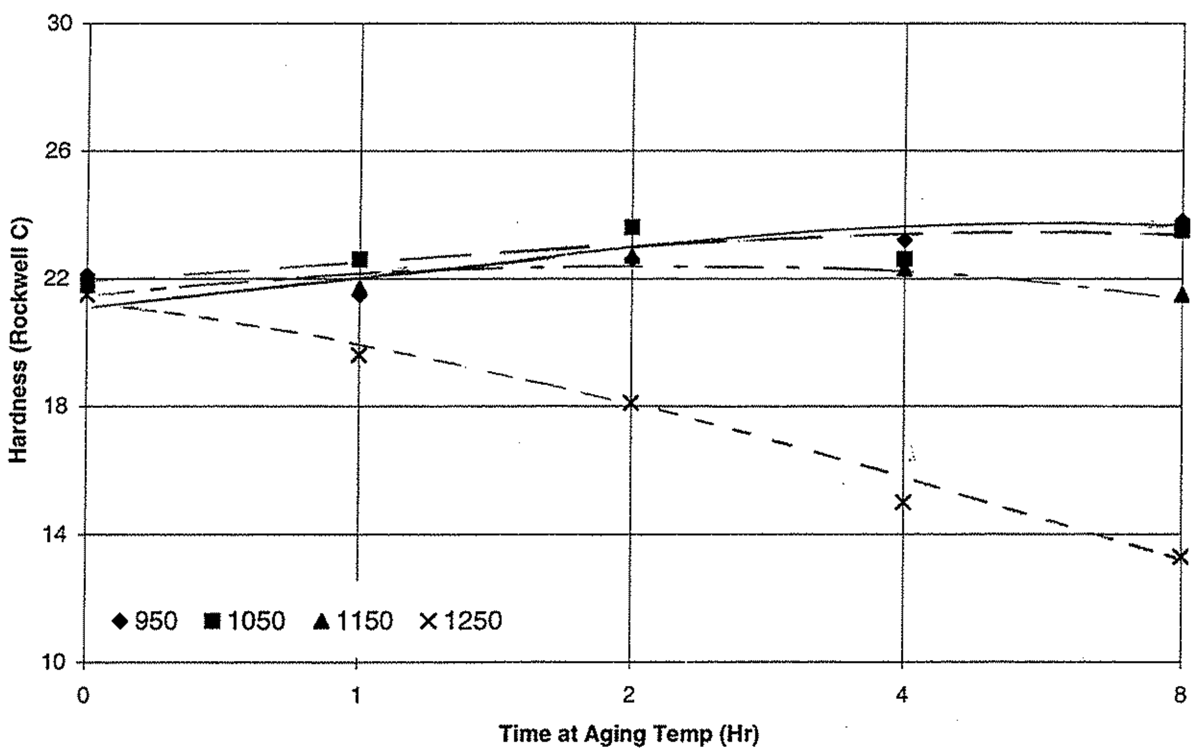

Figure 2b - The Effect of Aging Time and Temperature on Hardness of Steel M2, Water Quenched

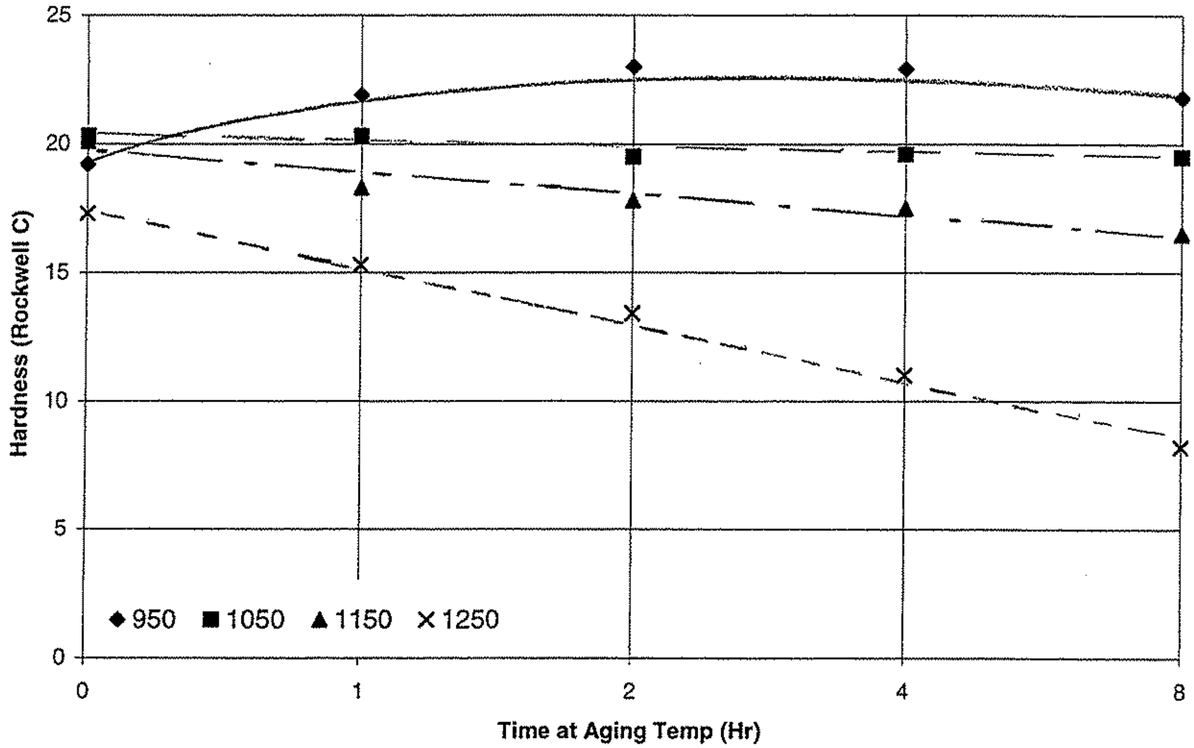

Figure 3a - The Effect of Aging Time and Temperature on Hardness of Steel B6, Normalized

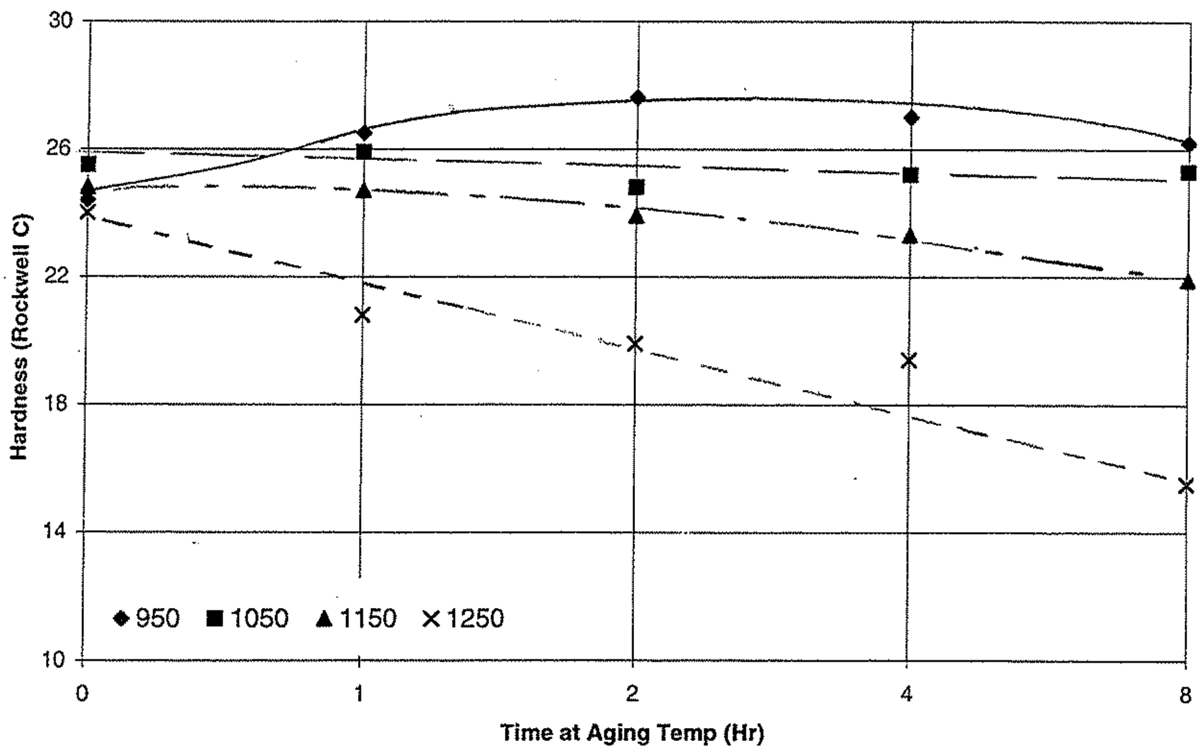

Figure 3b - The Effect of Aging Time and Temperature on Hardness of Steel B6, Water Quenched

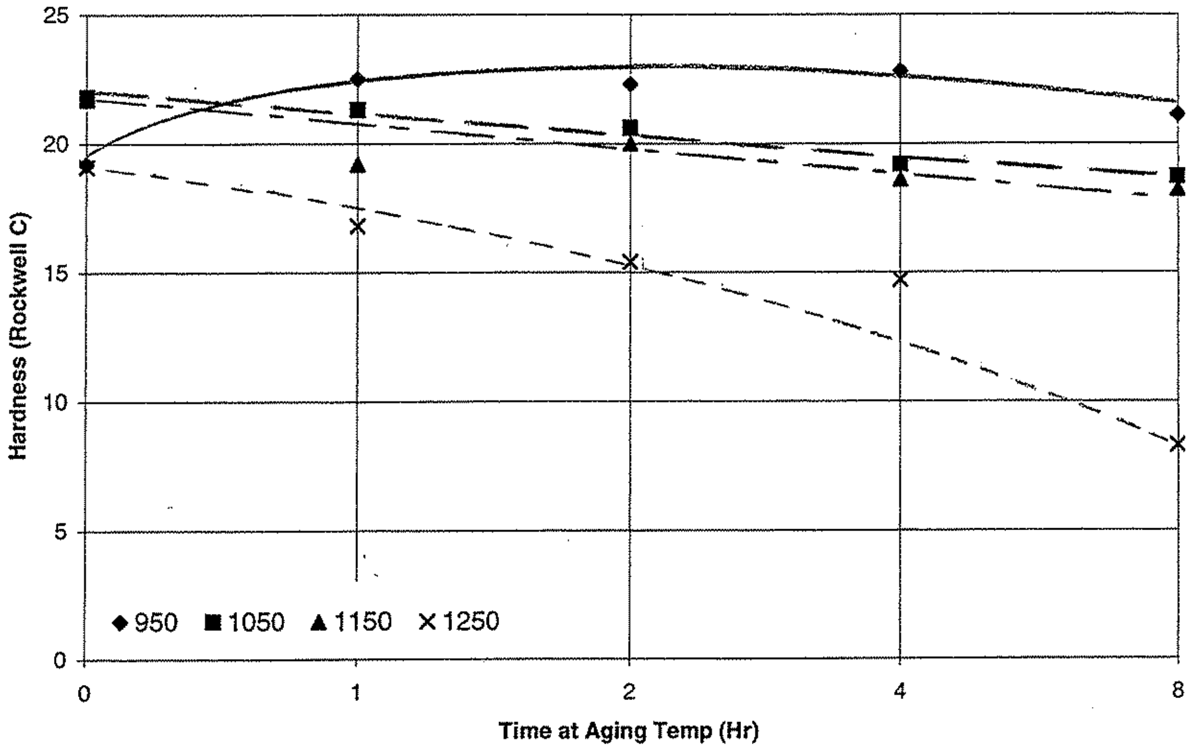

Figure 4a - The Effect of Aging Time and Temperature on Hardness of Steel M3, Normalized

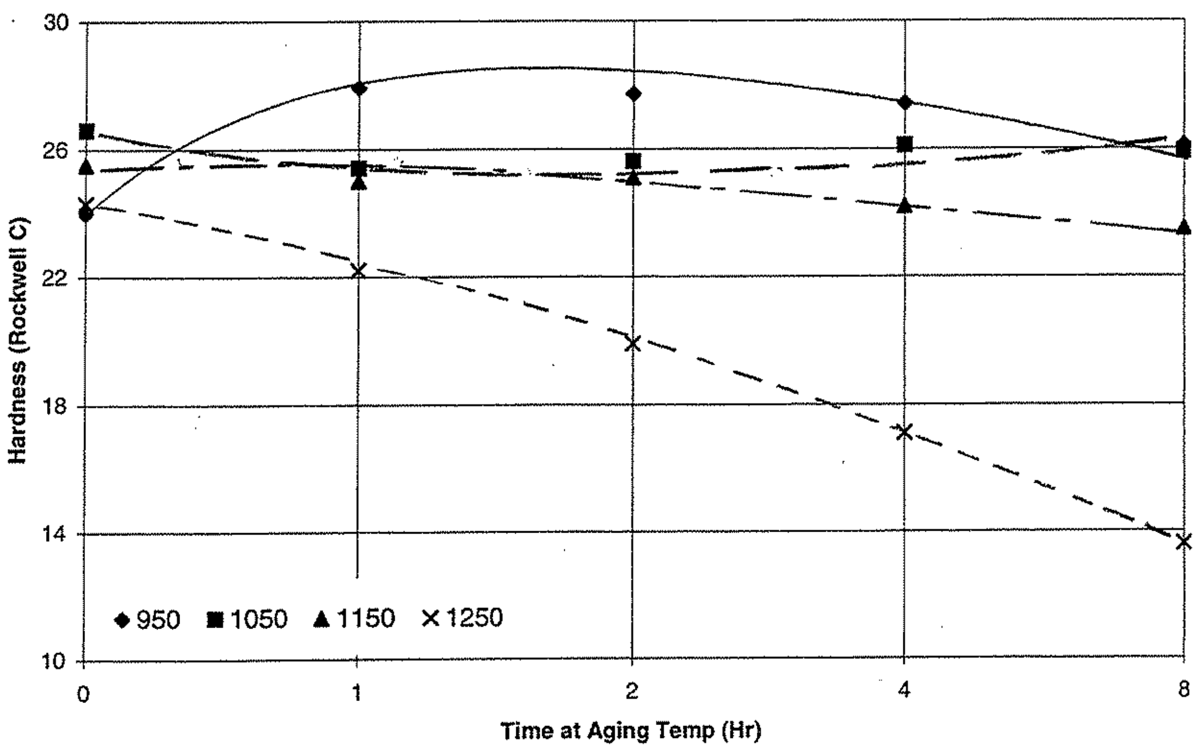

Figure 4b - The Effect of Aging Time and Temperature on Hardness of Steel M3, Water Quenched

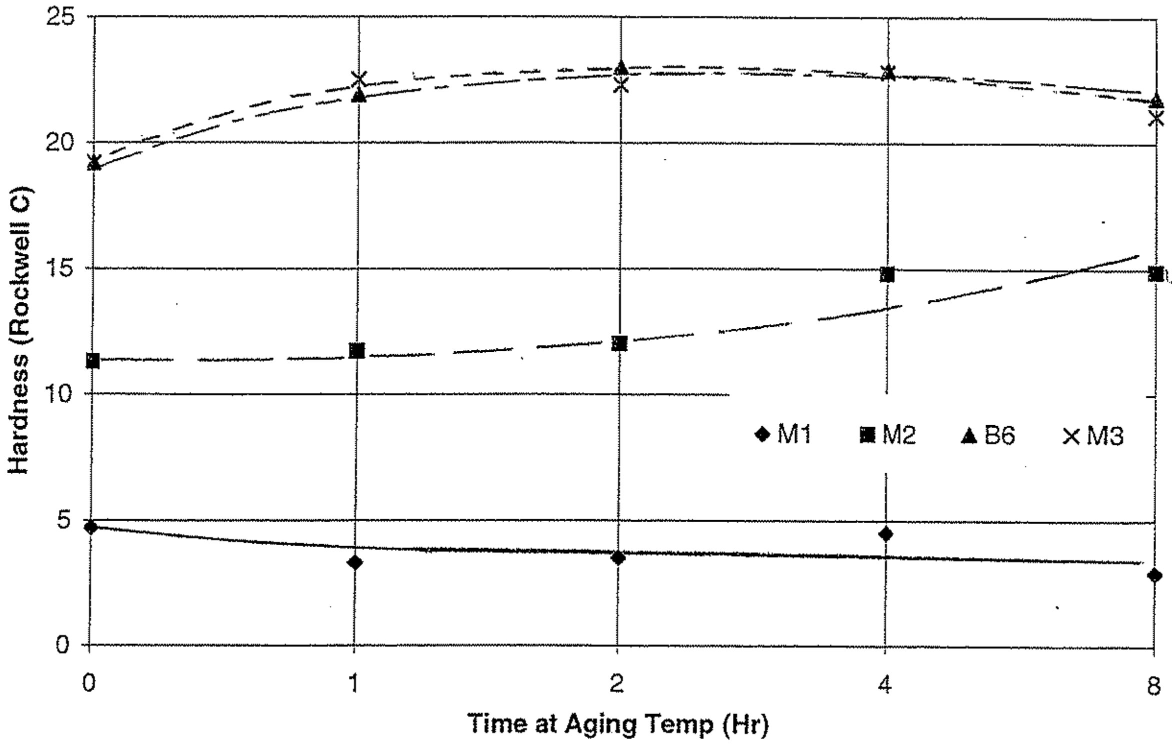

Figure 5a - The Effect of Copper Content and Aging Time at 950 F on Hardness, Normalized

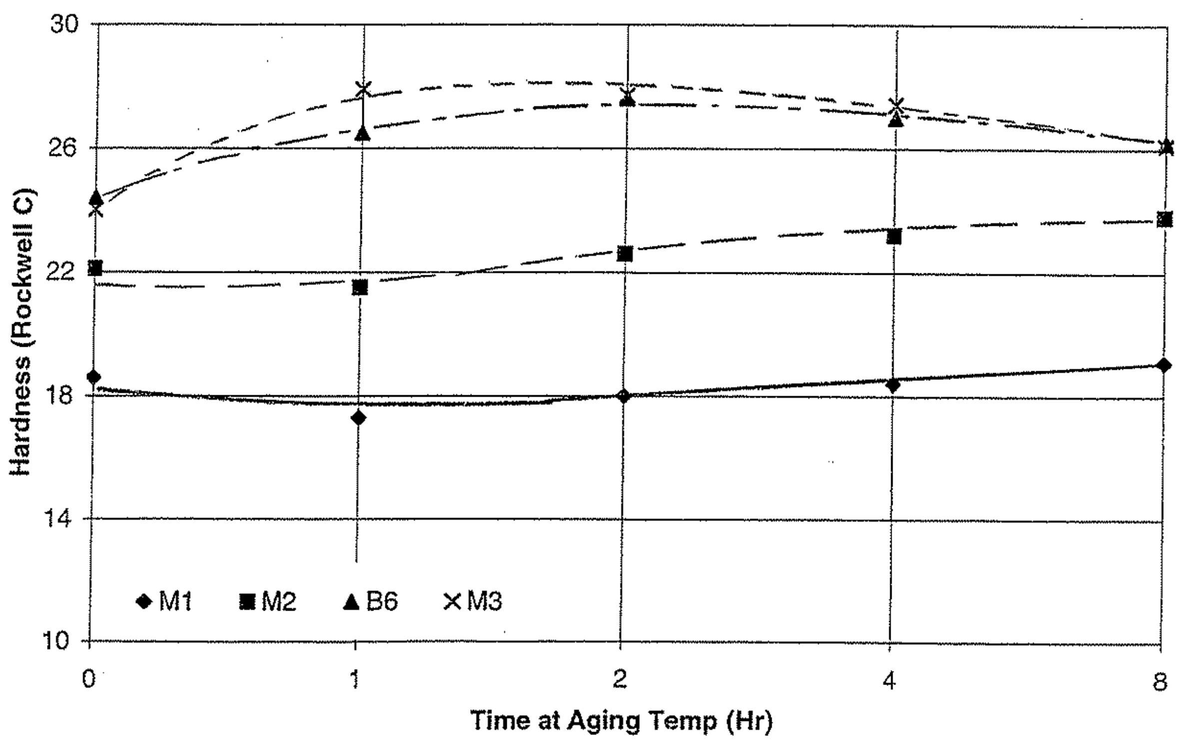

Figure 5b - The Effect of Copper Content and Aging Time at 950 F on Hardness, Water Quenched

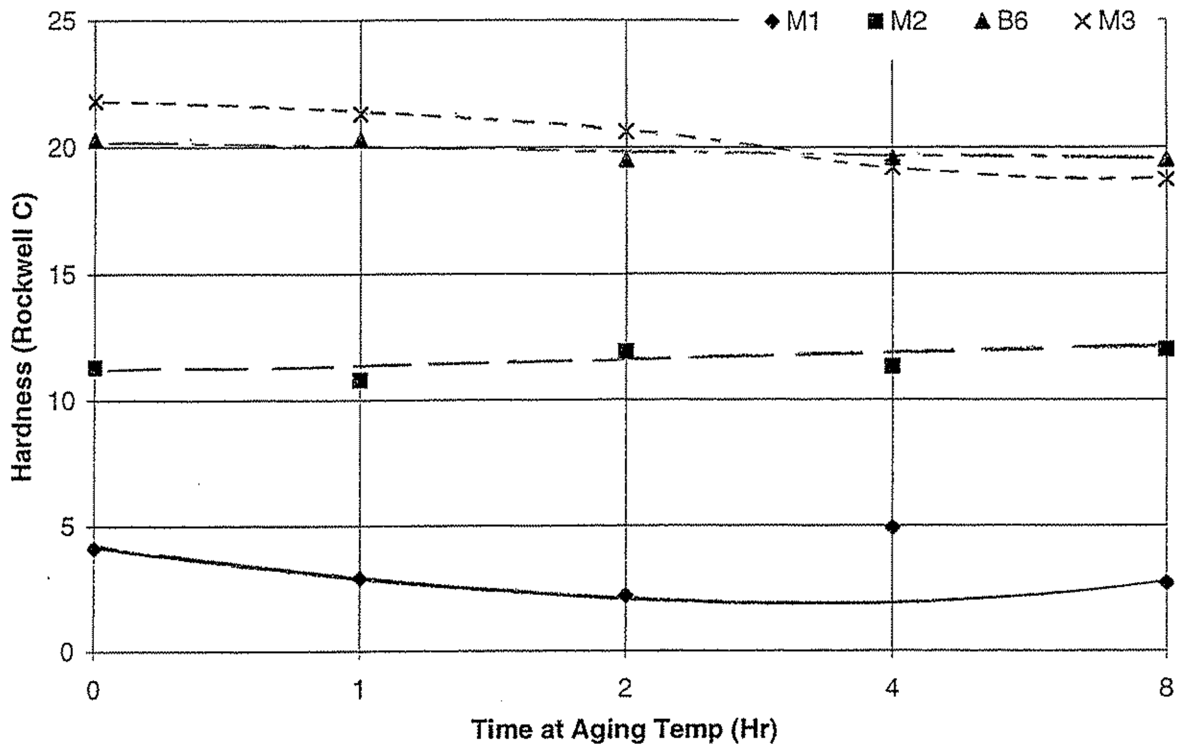

Figure 6a - The Effect of Copper Content and Aging Time at 1050 F on Hardness, Normalized

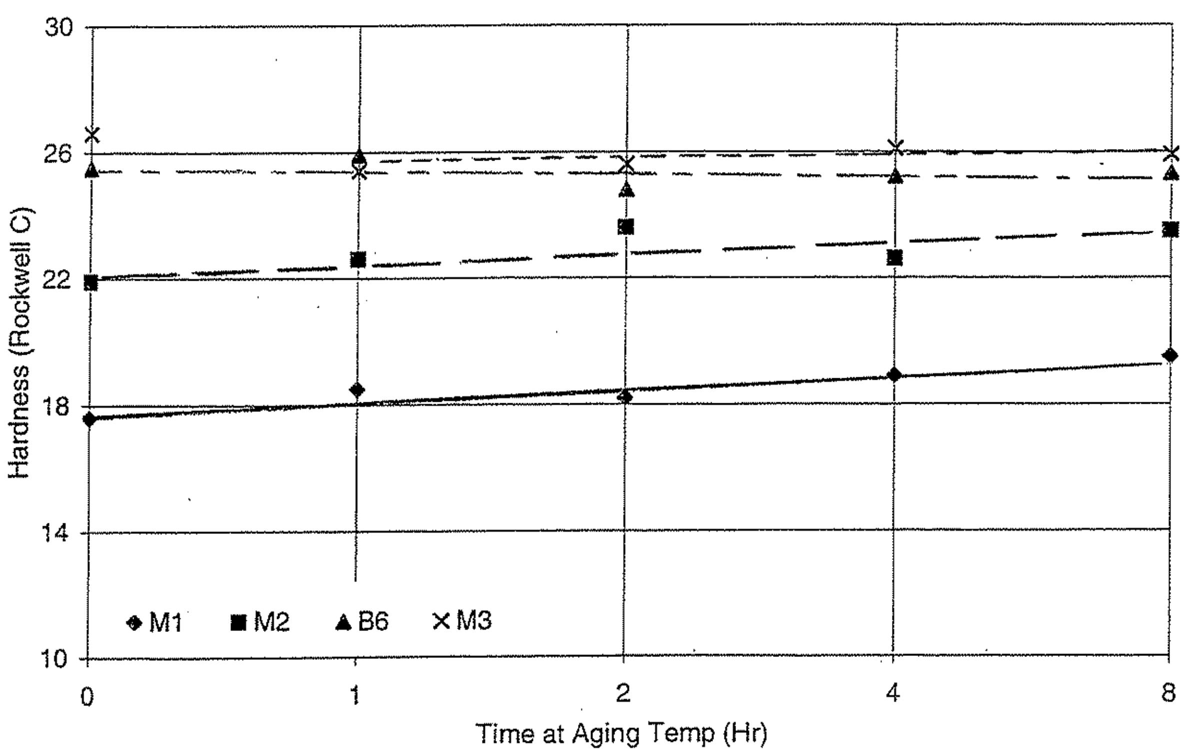

Figure 6b - The Effect of Copper Content and Aging Time at 1050 F on Hardness, Water Quenched

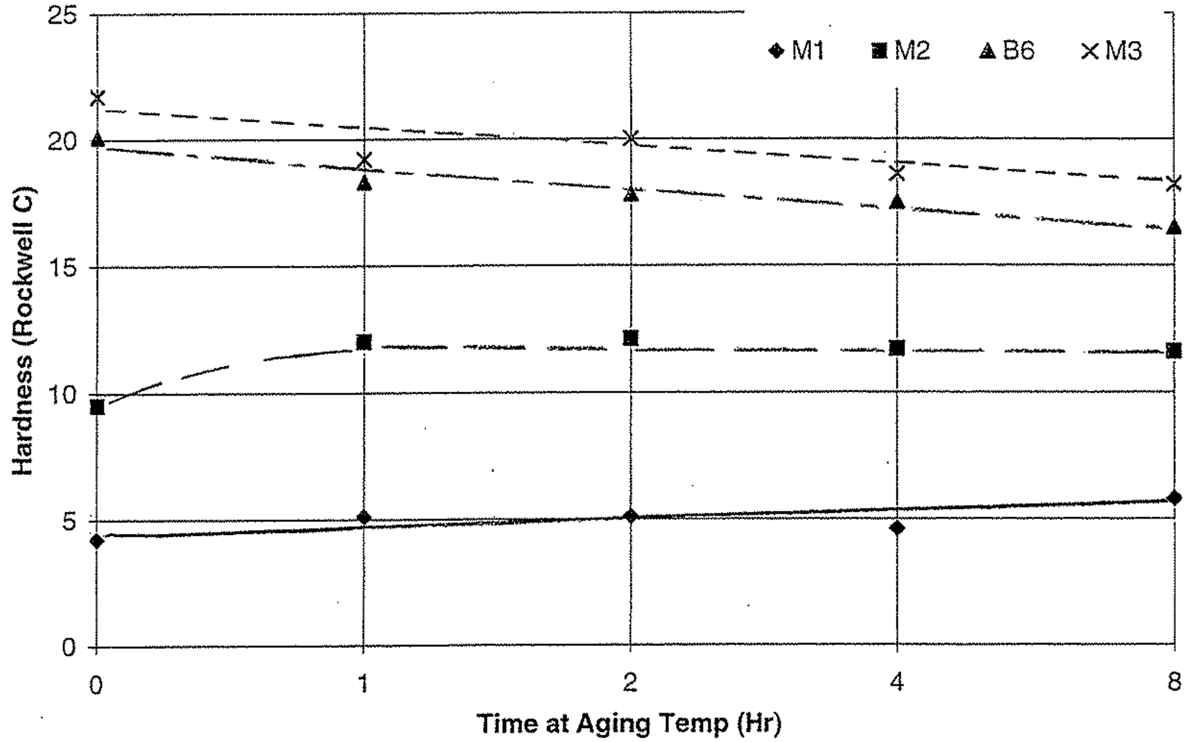

Figure 7a - The Effect of Copper Content and Aging Time at 1150 F on Hardness, Normalized

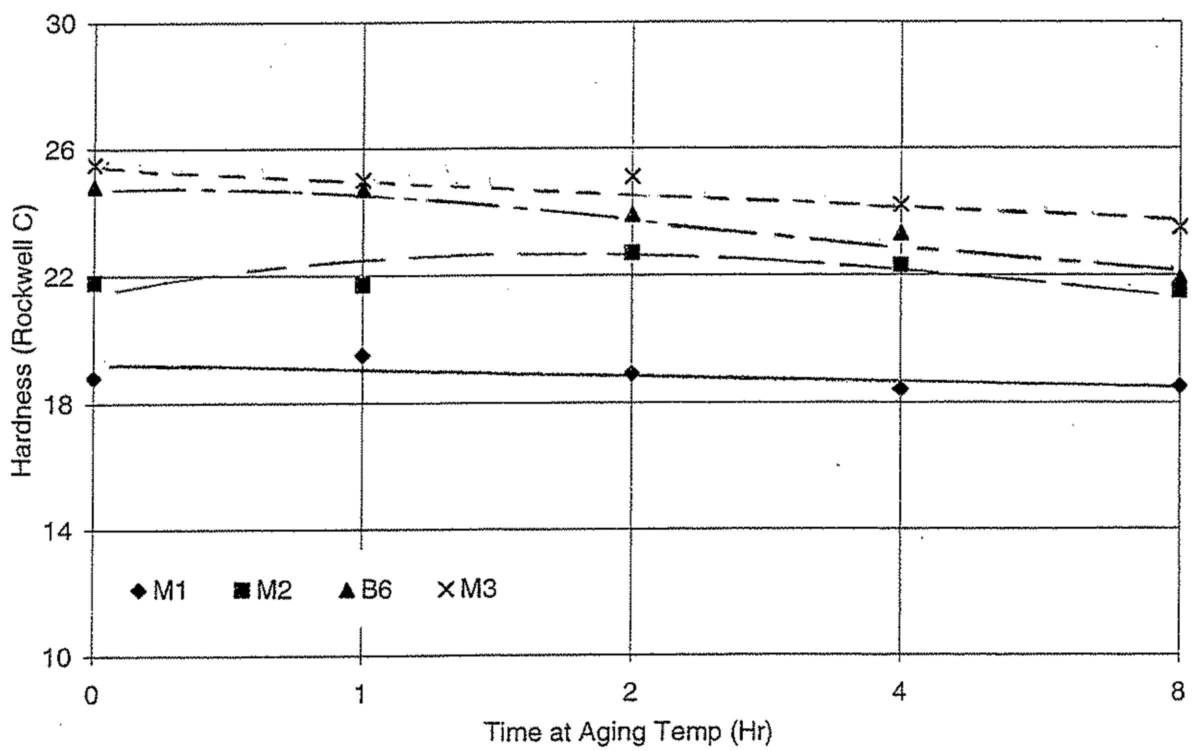

Figure 7b - The Effect of Copper Content and Aging Time at 1150 F on Hardness, Water Quenched

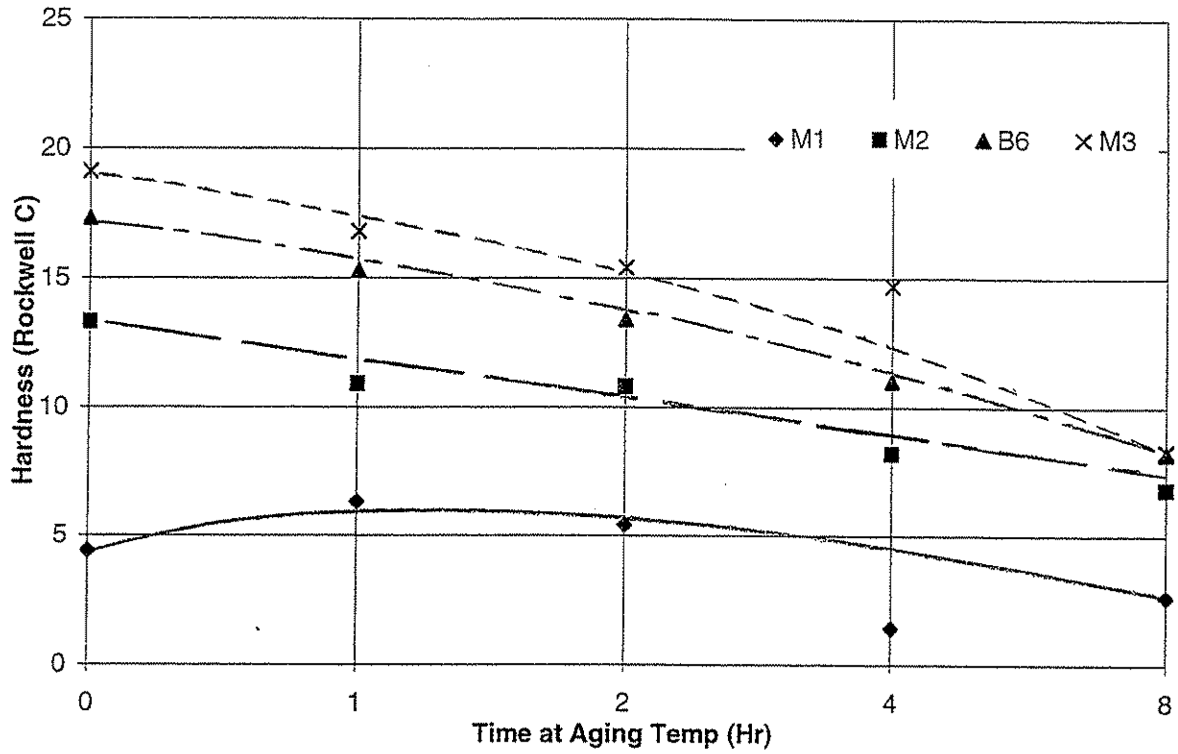

Figure 8a - The Effect of Copper Content and Aging Time at 1250 F on Hardness, Normalized

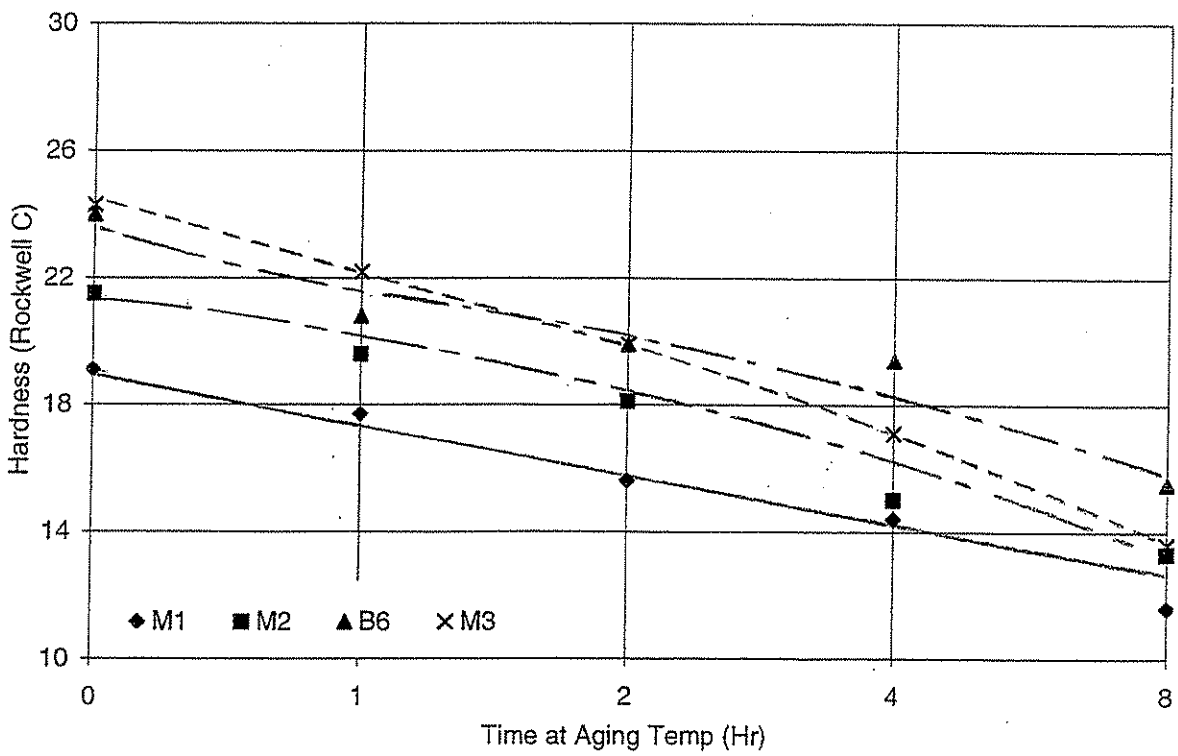

Figure 8b - The Effect of Copper Content and Aging Time at 1250 F on Hardness, Water Quenched

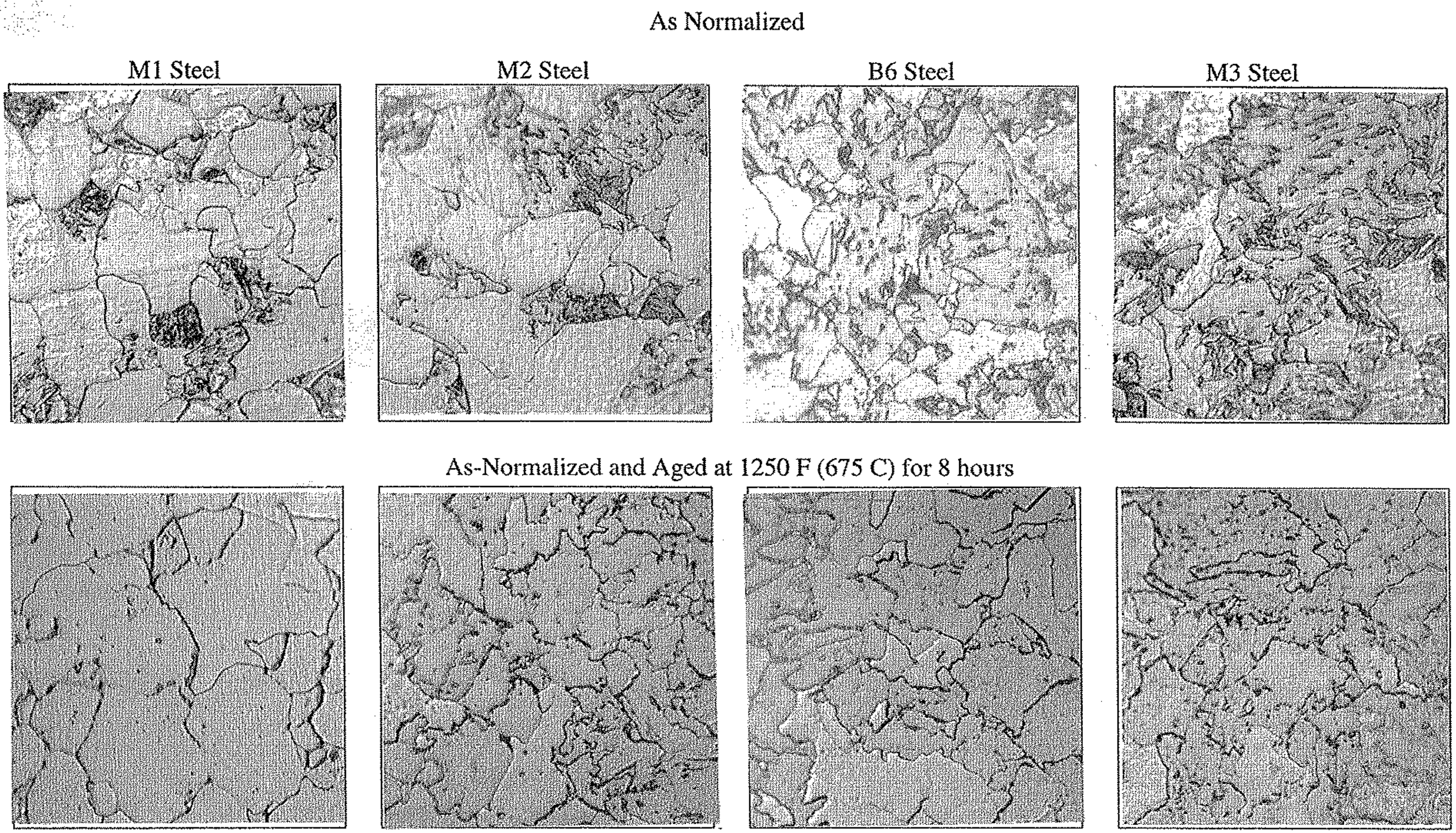

Figure 9 – Comparison of As-Normalized and Normalized and Aged Microstructures, 850X Nital-Picral

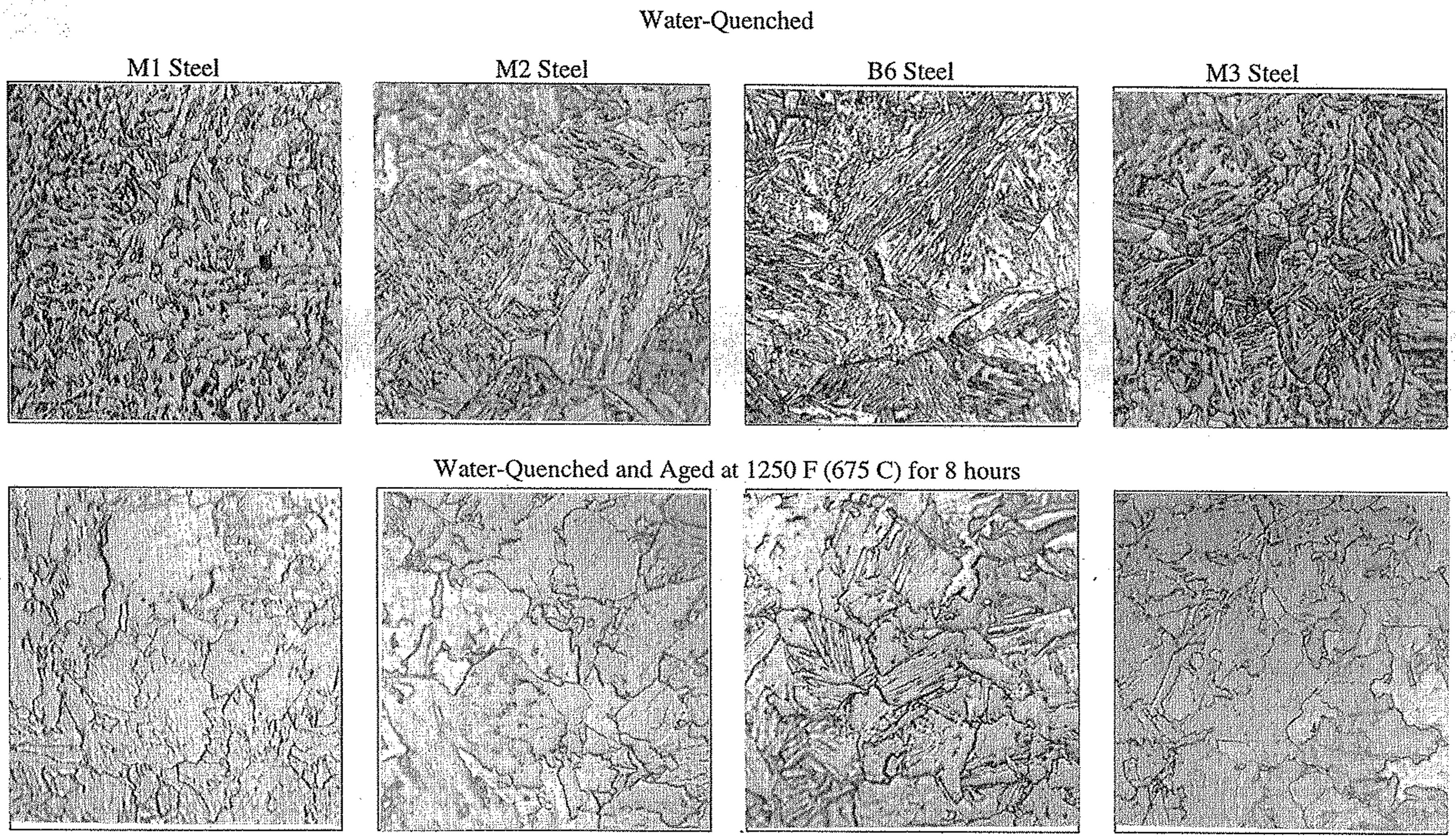

Figure 10 – Comparison of Water-Quenched and Water-Quenched and Aged Microstructures, 850X Nital-Picral